Novel Negative Pressure Wave-based Pipeline Leak Detection System Using Fiber Bragg Grating-based Pressure Sensors

Jiqiang Wang, Lin Zhao, Tongyu Liu, Zhen Li, Tong Sun and Kenneth T. V. Grattan

Abstract—**In this paper, the design and underpinning technical principles of the novel design of a negative pressure wave (NPW)-based pipeline leak detection (PLD) system has been reported, which is configured using Fiber Bragg Grating (FBG) pressure sensors. To evaluate this, a pipeline leakage test platform has been established and experiments have been conducted, to verify the performance of a system using this FBG-based approach. The results show that a system using FBG-based sensors can accurately determine the pressure change trends along the pipeline and thus allow the calculation of the NPW velocity online. A key comparison is made with traditional NPW detection techniques, showing that the novel detection system is capable of achieving the higher leak-location accuracy and the detection of smaller leakage volumes. This arises from the ability of the FBG-based system to allow an increased number of sensors to be multiplexed along the pipeline. Their corresponding output signals generated show a very satisfactory, high signal-to-noise ratio. The system has been evaluated, especially in its response to extraneous signals and thus disturbances caused by the pump starting or stopping can be eliminated. This was achieved through an analysis of the time sequence of the pressure changes captured by the multi-sensor array being carried out and thus immunity to such effects demonstrated. The system has thus been designed to minimize the instances where a false alarm occurs.**

Index Terms—**Pipeline leak detection (PLD), negative pressure wave (NPW), pressure sensor, fiber Bragg grating (FBG), pressure change.**

I. Introduction

PIPELINES represent one of the most economical solutions to transport large quantities of oil, gas, chemicals and water over land, with the advantages of large volume, continuous operation, low cost and freedom from climatic impact and other limitations [1]. Pipeline transportation has become the fifth major transportation method following roads, railways, waterways and aviation: it is often termed 'lifeline engineering'. The total length of pipelines constructed for transportation across the globe is approximately 3,800,000km, as of 2014 [2]. Many more pipeline projects are in the planning stage with others under construction currently, most of which are distributed in densely-populated areas. Pipeline incidents such as pipeline explosions, breaks, leakages, illegal drilling into pipes and stealing oil have occurred in recent years and can present a problem to users and to the environment. Apart from unwanted human interactions (such as accidental damage, theft or sabotage) these problems are typically caused by mechanical aging, construction defects and pipeline corrosion [3], [4]. As a consequence, an effective pipeline leak detection (PLD) system is essential. This is both to ensure effective transportation of what may be an expensive fluid over long distances and to avoid any possible hazards to the environment as a result of pipeline leaks.

The most effective pipeline detection techniques integrate knowledge that is both multi-disciplinary and multi-domain. At present, there are many methods and techniques reported for PLD [5], [6], the most important being leaking medium detection [7], [8], pipe wall parameter detection [9], the use of acoustic principles [10], [11], and optical fiber sensing detection [12], [13]. These methods differ in cost, effectiveness and applicability to different situations as well as how they may be deployed for long lengths of pipe, and in different weather or climatic conditions, for example.

The negative pressure wave (NPW) method is the most widely used, among all the acoustic methods and is based on the assumption that a leak occurs between two points where two pressure sensors are installed. The principle is as follows: based on the NPW velocity, the wave arrival time difference and the known distance between the two pressure sensors, the leak location can thus be determined. This method is sensitive, accurate, adaptable and does not require the establishment of a detailed pipe model. This forms the basis of the novel approach taken in this paper, which is original in the use of specially designed Fiber Bragg Grating (FBG)-based sensors to replace the more familiar piezo- or MEMS-based sensors used in conventional systems. This is not a trivial substitution but has required a careful redesign of the transducer to incorporate the FBGs and thus to take advantage of the characteristics of FBGs that piezo- or MEMS-based systems do not show – for example in the signal processing or the use of long distances between

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sensors. Further, a two-point pressure detection system has shown limitations due to the weak signals often generated – this work extends it to a multi-point system. In recent years, the research focus has often been on the signal extraction using various methods or algorithms [10], [11], for example, wavelet transform, fuzzy support vector machine analysis, empirical mode decomposition, Kalman filtering, etc, in order to identify the weak leak signatures. In addition, the familiar, traditional two-point pressure detection system may not function well due to what may be severe signal attenuation accompanying the need for increasing pipeline length. Tian *et al*. have proposed an approach in which the pressure sensors are distributed along the pipeline and simulation analysis has been carried out [11], but this system proposed still shows large location errors because the NPW velocity is assumed to be constant. Therefore, for long-distance PLD with accurate location identification, a new and improved method is required. This is achieved in the original approach in the work.

As a recent sensing technology, optical fiber methods have been widely reported and are suitable for PLD. Optical fiber-based methods offer a very satisfactory solution to measurement needs of this type: the sensors are physically robust and have the advantages of small size, light weight, resistance to corrosion and low signal loss [14]-[16]. The techniques reported in recent years for *fully distributed* fiber optic monitoring have mainly focused on the use of fiber optic sensor systems based on Brillouin scattering, Raman scattering or interferometry and these have been tested on some pipelines [12], [13]. However, such techniques have shown some limitations for practical use. The Raman scattering-based system can only monitor leakages which lead to temperature change and with the Brillouin scattering-based technique, the signal processing poses a major challenge. An interferometer-based system is typically susceptible to environmental changes which are not necessarily related to the leaks themselves and in many cases these systems, discussed above, are too expensive to implement when lower value fluids are transported.

By contrast, FBG techniques have been widely used and shown themselves robust for structural condition monitoring, due to their straightforward multiplexing capability, ease of the sensors being embedded, high reliability and moderate cost [17], [18]. Researchers have attempted to measure the PLD through the use of FBG-based sensing technology where, in the literature, a FBG strain monitoring device has been reported to measure the pipeline hoop-strain caused by the resulting pressure change [10], [19]. However such a simple approach is prone to false alarms because many different factors can cause pipeline strain, such as the temperature changes, vibration and so on and thus there are problems with its use in leak detection.

This paper proposes an innovative, robust and improved method to replace the two-point pressure sensor approach with a novel quasi-distributed multi-point pressure sensor scheme. To do so exploits the favorable characteristics of FBGs as the basis of the sensor system and through the use of transducers configured with that technology, establishes a novel NPW-based methodology well suited to pipeline leak detection, offering high accuracy and reduced false alarms.

II. Monitoring System Principle and Scheme

A. NPW-based Detection Principle

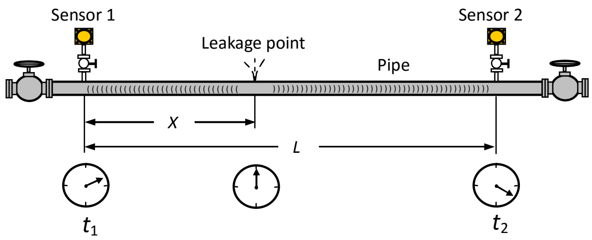


Fig. 1. NPW leak detection principle with a two sensor system, Sensor 1 and Sensor 2 [20].

Fig. 1 illustrates a schematic of a section of a pipeline where a leak occurs between two points where two pressure sensors are installed. In the presence of a leak, the pressure at that leakage point will drop and this pressure change will spread upsteam (towards Sensor 1) and downstream (towards Sensor 2) along the pipeline. This occurs at the same velocity as the acoustic wave travelling in fluid, this being the negative pressure wave. Based on the NPW velocity, the wave arrival time difference at the two pressure sensors and the (known) distance between the sensors, the leak location can thus be determined through the following analysis.

It may be assumed that the pipeline length is L, the flow rate of the medium in the pipeline is u and the flow direction is from Sensor 1 to Sensor 2, the NPW propagation velocity is v. The position of Sensor 1 is set as the reference starting point, the leakage point is assumed to be at position X and the arrival times of NPW at both ends of the pipe are t_1 and t_2, respectively. The following then apply:

$$t_1 = \frac{X}{v-u} \qquad t_2 = \frac{L-X}{v+u} \tag{1}$$

If $\Delta t = t_1 - t_2$, then the leakage point, X can be determined by using the following equation:

$$X = \frac{1}{2v}\left[L(v-u) + \Delta t\left(v^2 - u^2\right)\right] \tag{2}$$

In general, a typical NPW propagation velocity is approximately 900-1200m/s in oil and 1000-1500m/s in water. Compared to the above, the liquid flow rate u in the pipeline is typically within the range of 1-3m/s, which can be considered to be negligible. Therefore Eq. (2) can be simplified to:

$$X = \frac{1}{2}\left(L + v\Delta t\right) \tag{3}$$

From Eq. (3), it can be concluded that the accuracy with which the actual leak location can be determined is influenced by several key factors: the pipe length, the NPW velocity and the time difference measured for the NPW arriving at both ends of the pipe. In practical applications, the increase of the pipe length will cause signal attenuation of the NPW and thus a limitation in the use of such a two-point monitoring system.

In any practical pipeline system, there are sources of interference – thus not only the leakage itself but also the effects of the normal operation of the system (e.g., pump adjustment / start / stop) may also produce a NPW and this may cause a false alarm if not recognized. As a result, in traditional NPW-based systems, it may become difficult to identify whether the NPW is caused by leakage or one of these interfering effects, potentially causing false alarm errors.

B. NPW-based PLD System Using FBG Pressure Sensors

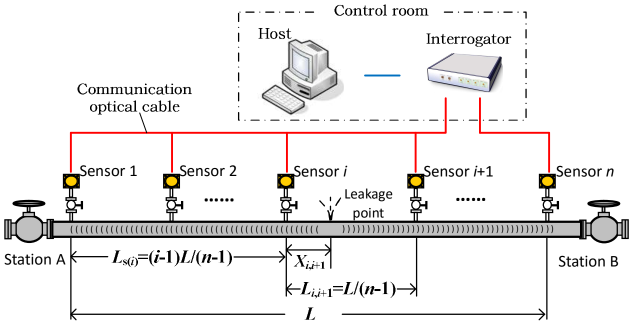


Fig. 2. Schematic of the PLD system using FBG-based pressure sensors.

Fig. 2 illustrates the novel NPW-based leak detection system, proposed in this work, to overcome the limitations discussed in the above (Section II (A)). The system has been designed to comprise an array of FBG-based pressure sensors, a transmission cable, a fast FBG interrogator, a monitoring host and the usual related instrumentation accessories. This approach takes advantage of the communication optical cable being present along the length of the pipeline as the signal transmission channel, and makes full use of the wavelength coding and multiplexing capabilities of the FBGs, whose transducer properties lie at the heart of the sensor system.

Each of the FBG-based pressure sensor devices used is configured as a robust unit which includes a beam, a bellows and two FBGs bonded symmetrically on opposite sides of the beam, as shown schematically in Fig. 3 (a) and in Fig. 3 (b).

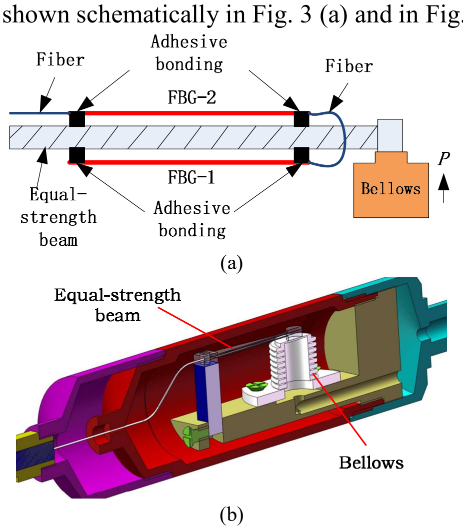


Fig. 3. Illustrations of the FBG-based pressure sensor designed: (a) Pressure sensing schematic; (b) FBG pressure sensor structure

The sensor operates as follows – when the medium inside the pipeline exerts a pressure change, ΔP, on the bellows, the deformation of the bellows disturbs the balance of the beam, which has been designed to be of 'equal-strength', thus allowing for the translation from the pressure change to the bending of the beam. The latter can be quantified by monitoring the wavelength shifts of the two FBGs in opposite directions. Both FBGs are specifically written into the optical fiber to have the same temperature coefficient, k_T, and strain coefficient, k_P, and the wavelength shifts of both FBGs caused by the environmental temperature effect would be identical. Therefore, the total wavelength shifts of the two FBGs can be described as follows:

$$\begin{aligned} \Delta\lambda_1 &= k_P \Delta P + k_T \Delta T \\ \Delta\lambda_2 &= -k_P \Delta P + k_T \Delta T \end{aligned} \tag{4}$$

where the subscripts, 1 or 2, on each $\Delta\lambda_{1,2}$ above signifies FBG-1 or FBG-2 respectively. $\Delta\lambda$ is thus defined as follows, showing a direct measure of the pressure change.

$$\Delta\lambda = \Delta\lambda_1 - \Delta\lambda_2 = 2k_P \Delta P \tag{5}$$

Thus this FBG-based pressure sensor unit not only offers a high sensitivity for pressure measurement, but also inherently overcomes the cross-sensitivity of FBGs to temperature variation by using the inbuilt differential structure. These sensors are not fragile to use and thus high sensitivity pressure sensors of this type may be installed at known intervals along the pipe, allowing a linear sensor array to be formed, as shown in Fig. 2.

C. Leak Location Identification

(i) Identification of the leak zone

The FBG-based pressure sensors discussed form the basis of the overall sensor system. The devices (which are shown in Fig. 3 were uniformly distributed along the pipes, and the outputs were connected to a fast FBG interrogator, in series or in parallel. The demodulation data obtained were processed through the development of a new software, following the scheme in the flow-chart shown in Fig. 4, by first identifying the zone where the leak occurs. Next the NPW method (discussed in detail in Section II (A)) is used to calculate the leak location to high precision.

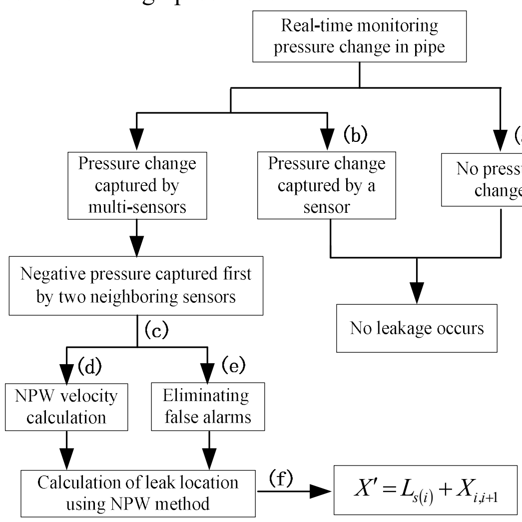


Fig. 4. Flow-chart for NPW leak location using FBG-based pressure sensors.

Fig. 4 shows the sensor response situation clearly: if there is no leak, none of the sensors picks up the negative pressure (point 'a' on Fig. 4) and if there is any interference, a single localized sensor only would indicate the change (point 'b'). If there is a leak, the NPW generated by the leak would first be monitored by the two neighboring sensors, between which the leak occurs (point ‘c’). Further, the closer the sensor is to the actual leak, the sooner it will capture the signal associated with the pressure change as the pressure wave spreads out. After the identification of the leak zone, the NPW velocity then is calculated (point ‘d’): this calculation takes into account any interference effects (point ‘e’). Finally Eq. (3) is used to calculate the location of the leak (point ‘f’ on Fig. 4).

(ii) NPW velocity calculation and elimination of false alarms

The NPW propagation velocity, v, in the pipe will vary with the temperature distribution and the pressure distribution along the pipeline – this velocity cannot simply be considered to be constant as various interference effects can influence it. For example, under normal working conditions (e.g., when the pump is starting or stopping), negative pressure can also be induced and this could be one of the main sources of false alarms. In addition, the effect of temperature on the NPW velocity must be considered; here v should not be considered as a constant even though there are temperature and / or pressure variations.

Using the setup discussed, a novel FBG-based approach to determine the NPW velocity is presented. This utilizes the distance of any two sensors from the leakage point and the time difference of the signals received at these two sensors capturing the pressure variation, thus

$$v_{l,l+m} = \frac{L_{l,l+m}}{\left|t_{l+m} - t_l\right|} \tag{6}$$

In Eq. (6), t_l, t_{l+m} are respectively the times at which the signal is received by Sensor l and Sensor $l+m$ (thus capturing the pressure variation) and $L_{l,l+m}$ is the distance along the pipe between the two sensors. Here l, m are positive integers ($1 \leqslant l \leqslant i-1$ and $2 \leqslant l+m \leqslant i$, or $i+1 \leqslant l \leqslant n-1$ and $i+2 \leqslant l+m \leqslant n$) and it is assumed that the leak occurs between Sensor i and the next sensor along, Sensor $i+1$).

A method to eliminate the false alarms that is important for the success of the scheme is proposed in this paper. To do so takes into account the output of another sensor, Sensor j (j=3, 4, …, i-1). The source of the pressure change is determined knowing the distance between the adjacent sensors ($L_{1,2}$ is the distance between Sensor 1 and Sensor 2, $L_{2,j}$ is the distance between Sensor 2 and Sensor j) and the time difference of the corresponding sensors capturing the pressure change. Thus if the time signal from the pressure change, captured by Sensors 1, 2 and j are respectively t_1, t_2, t_j, and

$$\frac{L_{1,2}}{t_2 - t_1} = \frac{L_{2,j}}{t_j - t_2} \tag{7}$$

then it can be concluded that the pressure changes are *not* caused by pipeline leakage but by extraneous ‘noise’ effects – such as is seen from the often routine operation of the pressure pump at Station A (as shown in Fig. 2). The disturbances caused by the pump at Station B could be eliminated by using the same method.

(iii) Leak location identification

Section (i) has shown the determination of the leak zone and Section (ii) the calculation of NPW velocity and elimination of false alarms. Now the leak location can be calculated accurately using Eq. (3). As illustrated in Fig. 2, the leakage point has been determined (in a preliminary estimation) to lie at a point between Sensor i and Sensor i+1. Thus the length, $X_{i,i+1}$ represents the distance between the leakage point and the monitoring starting point (at Sensor i, where the distance to Sensor 1 is $L_{s(i)}=(i-1)L/(n-1)$) – it can be obtained using Eq. (3).

$$X_{i,i+1} = \frac{1}{2}\left(L_{i,i+1} + v\Delta t_{i,i+1}\right) \tag{8}$$

In Eq. (8), $\Delta t_{i,i+1}$ is the time difference determined from the signals at the two sensors first capturing the pressure change, and $L_{i,i+1}$ is the distance between the two sensors, $L_{i,i+1}=L/(n-1)$. So the distance of the leakage location from Sensor 1 can be expressed as:

$$\begin{aligned} X' &= L_{s(i)} + X_{i,i+1} \\ &= \frac{i-1}{n-1}L + \frac{1}{2(n-1)}L + \frac{v\Delta t_{i,i+1}}{2} \\ &= \frac{(2i-1)L}{2(n-1)} + \frac{v\Delta t_{i,i+1}}{2} \end{aligned} \tag{9}$$

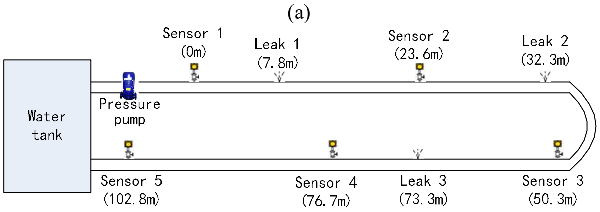
III. Pipeline Leak Test Platform and Experimental System

A. *Pipeline Leak Test Platform*

TABLE I
PIPELINE LEAK TEST PLATFORM PARAMETERS

Parameter	Value
Pipe diameter	100mm
Length	112m
Material	Carbon steel
Young's modulus	2.0-2.1*10^5MPa
Wall thickness	2mm
Leak hole diameter	32mm (Adjustable)
Operation pressure	0-0.4MPa
Tank volume	1*1.4*1.5m^3

(a)



(b)

Fig. 5. Pipeline leak test platform: (a) photo of the test platform; (b) pipeline layout with ‘artificial’ leaks built in at various known points.

To evaluate this, a pipeline leak test platform was constructed, using water as the fluid and transmission medium, and composed of a water tank, a pressure pump, a section of pipeline with 5 sensor mounting holes and 3 simulated leaks, and a pipeline-pressure adjusting device. The detailed specifications are given in Table I. The pipeline is arranged in a spiral shape, and supported by steel brackets, as illustrated in Fig. 5 (a). In addition, a standard pressure gauge and a standard commercial flow meter are installed in this platform for cross-comparison. The positions of the 5 sensor mounting holes and the 3 simulated leaks are as shown in Fig. 5 (b).

B. FBG-based Pressure Sensors Calibration

To evaluate the performance of these sensors the following procedure is applied. Standard, known pressures in the range from 0.1MPa to 1MPa are applied to enable an accurate calibration of 5 similar FBG-based pressure sensors (of the type shown in Fig. 3) and a linear fitting is carried out (using the least squares method) of the data. Using the information from this calibration, the appropriate fitting coefficients and the correlation coefficients for these 5 sensors were obtained and are shown in Fig. 6. The data from this figure indicates that the sensor network installed on the pipeline can achieve both good pressure sensitivity and linearity in performance.

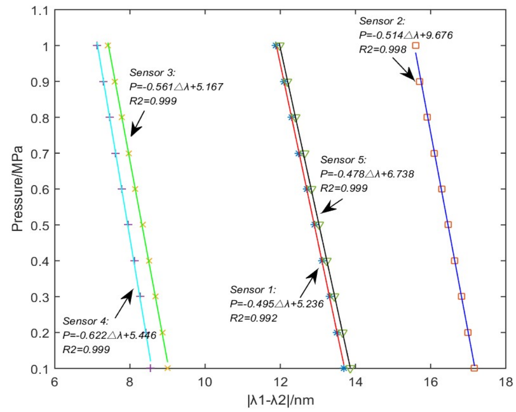


Fig. 6. Calibration of five different pressure sensors of the type shown: fitting between the calibration pressure and the measured value of $\Delta\lambda$.

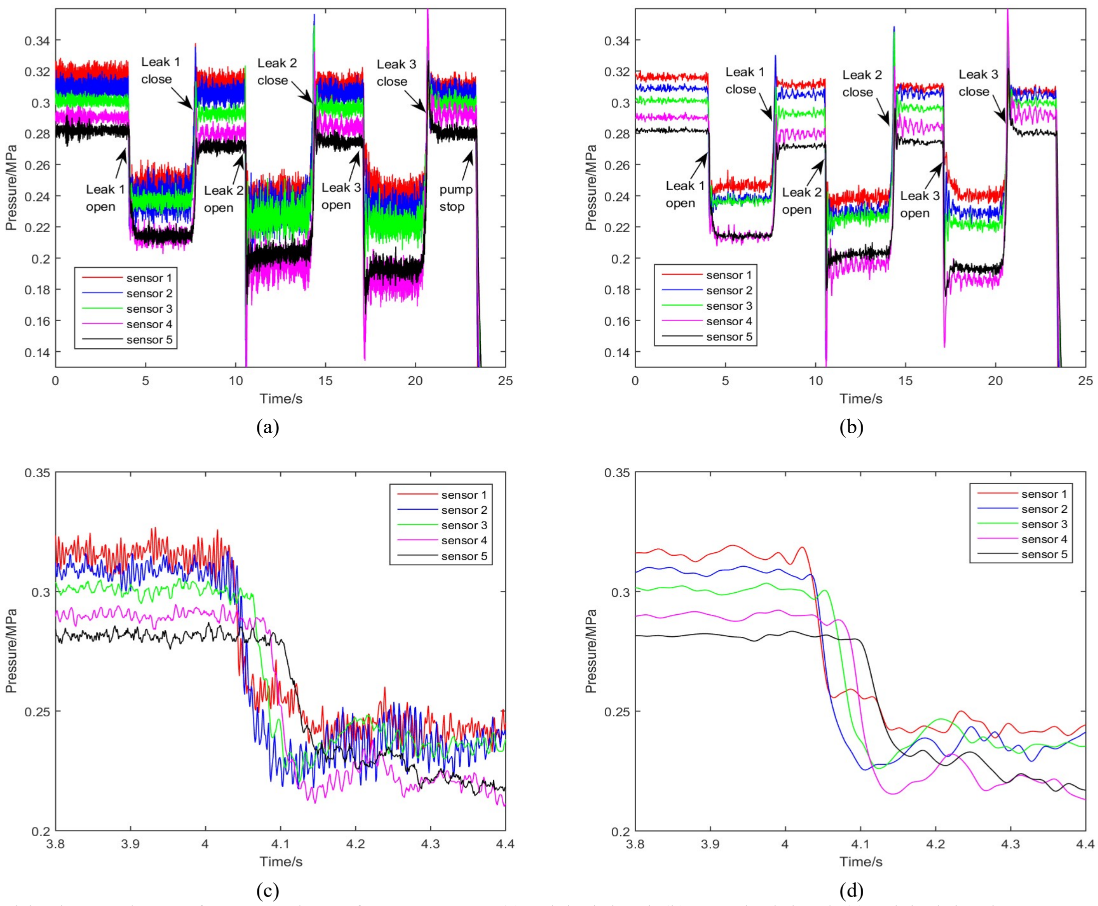


Fig. 7. De-noising by wavelet transform: In each case for Sensors 1 – 5 (a) Original signal; (b) De-noised signal; (c) Original signal at pressure change; (d) De-noised signal at pressure change

C. Sensors and Wavelength Interrogation

A NPW-based PLD system using the FBG-based pressure sensors described above has been set up, with the sensors placed as shown in Fig. 2. In this system, the 5 pressure sensors, calibrated as described before (from the data in Fig. 6), are installed along the pipeline, with their wavelength outputs monitored using the same 8-channel interrogating system (type GC-97001C-8, with a scanning frequency of 1000Hz and supplied by Arcadia Optronix Company, Zhuhai City, China). With a fiber length of less than 50m, the optical signal transmission delay in the fiber is assumed negligible.

D. De-noising by Use of a Wavelet Transform Approach

An important consideration when using the NPW-based PLD method is to detect, as accurately as possible, the pressure change point associated with the leak, in the knowledge that extraneous noise will cause errors. Therefore it is necessary to minimize the noise to achieve greater measurement accuracy and to do so, the wavelet transform method is used to filter the signals received. This approach has excellent characteristics of time-frequency localization, and benefits the measurement through enabling the key features of the signals received to be more evident, while at the same time effectively reducing the interfering noise signals.

E. Experimental Measurement Parameters

The experiment carried out had the following experimental parameters: a starting pressure of 0.32MPa; a water temperature of 16℃ and an average flow rate of 29.5m^3/h. The 3 valves which were used in the pipeline (Fig. 5) to simulate a leak were fully opened and then closed successively, following which the pressure pump was shut down. The signal data received from the 5 pressure sensors, located as shown in Fig. 5(b), are illustrated in Fig. 7. Analyzing the results, it can be seen that Fig. 7 (a) shows the original pressure signals collected by all the 5 installed sensors and Fig. 7 (b) indicates the 'de-noised' signal, after applying a 4-layer decomposition by using the 'sym8' wavelet. It can be seen that the result of de-noising is successful in providing the greater clarity needed to allow the simulated leak situation to be well understood. Details of the differences can be seen when the original and de-noised signals are amplified, being monitored at the time of opening valve 1, as shown in Fig. 7 (c) and (d). As clearly indicated in Fig. 7 (d), the first two sensors to receive the negative pressure signals are Sensors 1 and 2, indicating that the leak is located in the zone between these two sensors. The analysis further confirms the value of the wavelet de-noising approach, as it yields excellent performance in maintaining the desired local signal characteristics at the pressure change. This then allows the next step in locating the leakage points precisely to be taken.

F. NPW Velocity Calculation

The NPW velocity can be calculated using Eq. (6). Here Table II shows the time measured for the arrival of the first pressure change signal at the 5 different sensors (when, in this experiment, the simulated leak is caused by the opening of valve 1).

In this simulation, the pipeline length in the test platform is comparatively short (at just over 100m), so small deviations in the time difference of the pressure change signals received from the two sensors may cause larger errors in NPW velocity calculation (using Eq. (6)) than would happen in practical situations where the pipeline length is much longer (many hundreds of meters, or kilometers). To decrease the measurement error, the NPW velocity can be determined from a knowledge of the distance between Sensor 2 and Sensor 5 and the time difference between the signals received from the two sensors capturing the pressure change (together with a knowledge of v=1277.42m/s).

TABLE II
TIME FOR THE PRESSURE CHANGE SIGNAL TO ARRIVE AT THE 5 SENSORS

Sensor number	1	2	3	4	5
Sensor location (m)	0	23.6	50.3	76.7	102.8
Time for pressure change signal (s)	3.767	3.773	3.794	3.815	3.835

Assuming j=5 in Eq. (7) and the data recorded in Table II may then be substituted into Eq. (7), where the following can be obtained:

$$\frac{L_{1,2}}{t_2 - t_1} = 3933.33\ m/s$$
$$\frac{L_{2,5}}{t_5 - t_2} = 1277.42\ m/s \tag{10}$$

As it is evident that the two values are not equal, it can readily be deduced that the pressure change is caused by leakage occurring between Sensor 1 and Sensor 2.

G. Leak Location – Experimental Evaluation and Comparison of 'Traditional' and Novel FBG-based Sensor Systems

TABLE III
TRADITIONAL NPW-BASED METHOD

Leak position (m)	0.32MPa		0.25MPa		0.13MPa	
	Location (m)	Relative error	Location (m)	Relative error	Location (m)	Relative error
7.8	7.3	0.49%	8.6	0.78%	8.6	0.78%
32.3	31.9	0.39%	31.8	0.49%	32.5	0.19%
73.3	72.2	1.07%	70.9	2.33%	69.7	3.50%

TABLE IV
NOVEL NPW-BASED METHOD USING FBG PRESSURE SENSORS

Leak position (m)	0.32MPa		0.25MPa		0.13MPa	
	Location (m)	Relative error	Location (m)	Relative error	Location (m)	Relative error
7.8	7.9	0.10%	7.40	0.39%	8.1	0.29%
32.3	31.2	1.07%	32.4	0.10%	32.6	0.29%
73.3	73.3	0.00%	73.5	0.19%	73.4	0.10%

A comparison is now made between the results from a 'traditional' NPW-based PLD unit (composed of Sensor 1 and Sensor 5) and the average NPW velocity v=1259.2m/s at 0.22MPa (this being used as the reference velocity) and the novel NPW-based PLD system, composed of Sensors 1-5. Tables III and IV show the comparison of the performance of the leak locating methods and the accuracy in leak location obtained. This is compared to the 'traditional' NPW-based method (Table III - using Eq. (3)) and the novel NPW-based method (Table IV – using Eq. (9)). From the data in the Tables, it can be seen that the location error using the 'traditional' system increases approximately with the decrease of pipe pressure, but the novel method based on the quasi-distributed FBG pressure sensors is less affected by the pipe pressure change, and has higher location accuracy than the 'traditional' method. This validates the use of the novel FBG-based

IV. CONCLUSIONS AND FUTURE WORK

In this paper, a novel NPW-based PLD system using specially-designed quasi-distributed FBG pressure sensors has been reported, and used to monitor the pressure distribution of the medium used in the pipeline. The feasibility of this innovative approach and the high pipeline location accuracy have been verified by a series of experiments, using a special pipeline creating a simulated leak-test platform. The detection system implemented can accurately determine the pressure change trends along the pipeline and allow the calculation of the NPW velocity. Also, this novel detection system is capable of achieving the high leak location accuracy required, as well as enabling the monitoring of smaller leakage levels, due to the reduction of the signal attenuation which is monitored. This is done through increasing the sensor location density along the pipeline. At the same time, noting the time sequence of the pressure changes captured by the linear sensor array, the signal interference effects (such as are caused by the starting or stopping of the pump) can be reduced and therefore the leakage false alarm rate is reduced. All these are positive features of the FBG-based sensor system discussed in this work.

The evaluation was carried out in the laboratory, and at a controlled room temperature. It is well known that the NPW velocity and the NPW signal characteristics will vary with the temperature of the medium [21]. Future work will tackle this aspect through the addition of FBG-based temperature sensors to the system. Thus the temperature distribution along the pipeline can additionally be obtained and where needed a correction applied before the pressure change data are calculated. On-going work will also look to support the experimental research with the development of a more complete mathematical model for the pipeline operation, based on this type of quasi-distributed pressure and temperature distribution information. Thus the overall aim is for better pipeline integrity monitoring and to be able accurately to locate and tackle leak incidents.

V. ACKNOWLEDGMENTS

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